

Fault displacement hazard at natural gas storage fields-a future research and regulatory direction.

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Gas fields, Aliso leak, fault hazard, and regulatory direction: In the US over 400 natural gas storage fields supply nearly one-third of our nation's energy needs. That share is expected to grow in response to low-carbon fuel demands driven by climate change concerns, ample domestic supplies, and recent regulations. Natural gas (methane) provides fuel for electrical generation and heating and is often described as the low carbon bridge fuel from carbon intense coal and oil to renewables. While underground gas storage fields add flexibility to our energy system by providing ample supplies during periods of high demand they keep energy costs low by buying and storing during periods of low demand. As with most energy sources, natural gas comes with its own set of challenges: for example, the largest methane leak in US history recently occurred at the Aliso Canyon Gas Storage Field (ACGSF, aka Porter Ranch), California. Taking almost four months to control, the ACGSF leak demonstrated the difficulty of stopping an underground leak from one well in a pressured and large volume storage field. The leak underscores the need to evaluate all hazards and risks to gas storage fields and wells to avoid future environmental and societal damage, and the disruption of a needed source of energy and the waste of a valuable resource. The American Petroleum Institute RP 1171 (API 2015), that is guiding State of California and Federal new rule-making states "Depleted hydrocarbon reservoirs are candidates for natural gas storage because the reservoir integrity has been demonstrated over geologic time by hydrocarbon containment at initial pressure conditions." True, but gas wells at storage reservoirs have not existed over geologic time. A hazard such as fault displacement across a high pressure gas well during an earthquake could result in the rapid release of large volumes of methane to the atmosphere. If fault displacement is across many wells there is the potential for a methane release of much greater magnitude and difficulty to control than the recent leak at the ACGSF. In response to the ACGSF leak new recommendations, rulemaking, and policies for gas storage fields are being discussed and proposed at the industry advisory, State, and Federal levels in order to prevent the recurrence of such an event. While this direction is useful it is focused on well design and integrity, but a broader approach is needed where fault displacement hazard and risk are identified and evaluated. For example, in California several large gas storage fields, adjacent to urban areas, are developed across or close to potentially active faults capable of generating moderate to large earthquakes with up to several meters of fault displacement, yet the seismic risks to gas well integrity, the environment, and the nation's energy supply are poorly understood. Fault displacement hazard analysis (FDHA and PFDHA; Youngs, et al., 2003; Wells and Kulkarni, 2014) with its emphasis on the quantification of the distribution and variation of fault displacements, site-specific probabilistic analysis, design of infrastructure, and risk assessment could play a very important role in evaluating the safety of natural gas storage fields-if the approach is modified for the subsurface setting

and gas well design. Incorporation of FDHA into risk evaluations of gas fields and wells will probably require changes in the State and Federal regulations given the past lack of attention to this hazard. For instance, there is no public record of the operator at ACGSF, the Southern California Gas Company, or the State regulators of wells and gas fields, the California Division of Oil & Gas (DOGGR) and the California Public Utilities Commission, recognizing or evaluating the fault displacement hazard to the gas storage field and wells by the Santa Susana fault (SSF). Yet the SSF's existence and location within the ACGSF and prior oil field has been known to geologists since the late 1930s, and the California Geologic Survey's mapping shows that a segment of the fault, that is within a few kilometers of the field, ruptured the surface during the 1971 Sylmar earthquake ($M_w=6.4-6.7$), and the surface segment of the fault closest to the ACGSF has had Holocene movement. This lack of attention is now addressed in proposed regulations by DOGGR that will require the operator to identify hazards and submit a risk management plan that includes mitigation, and adding FDHA could fill a key safety and environmental need. On the Federal level, the passage in June 2016 of the US PIPES Act provides a two year open window for technical input and to influence new nation-wide regulations being formulated by the Pipeline and Hazardous Material Safety Administration (PHMSA) for natural gas storage fields. Inclusion of FDHA into Federal regulations would provide a uniform environmental and safety standard across the nation. PHMSA already has regulations and guidelines for surface gas pipelines crossing potentially active faults (PHMSA, 2011) and extension of that role to the subsurface makes sense given the much more difficult work of controlling leaks from gas wells compared to surface pipelines. **ACGSF example:** The ACGSF leak not only shows the impact of a lengthy, uncontrolled gas flow from just one well adjacent to an urban area (DOE, 2016), but it also focuses attention on the fault displacement hazard along the SSF (DOE, 2016, pg 61). It should be noted that the ACGSF leak is probably the result of casing corrosion pending on-going investigations and probably not due to movement on the SSF as no other wells crossing the SSF leaked, and there was no nearby earthquake at the initiation of the leak. Following are some of most significant impacts of the leak as of July 2016 (Harris and Walker, 2016): ~8,000 residents were relocated, ~ 5 Bcf of methane released to the atmosphere, operator has spent \$550 MM dealing with the leak, 25 + class action suits against the operator were active, and the substantial cost of the lost commodity (methane). During the leak numerous surface control attempts failed (top kills) and aggravated the leak that went from 2.0 to 25-60 MMcfd (DOE, 2015), and the leak was finally stopped by a relief well that took over two months to drill. **The Santa Susana fault displacement hazard:** The conclusion that the SSF is a displacement hazard at the ACGSF is based on the following (Davis, 2016): 1) All of the 114 Aliso Canyon gas storage wells that were active in 2015 intersect the SSF. 2) Many of the fault intersections are at shallow depths (less than 500 m below the surface) and there are several potential conduits for gas migration to the surface from a damaged high pressure gas well: the strata from just above the SSF to the surface are highly-fractured and dominated by vertical fracture sets; the SSF

zone is a thick band of shear-fractures that comes to the surface near the Porter Ranch community; and the Aliso leak showed that gas can flow to the surface just outside of the well casing. 3) The California Geologic Survey (CGS) recognizes, via the Alquist-Priolo Act (AP), that the SSF's eastern segment is an earthquake and fault-rupture hazard based on surface offset during the 1971 Sylmar earthquake. 4) The various slip rate estimates for the SSF are high. The 2015 Third Uniform California Earthquake Rupture Forecast, or "UCERF3," slip average is 2.9 mm/yr for the SSF. Yeats (2001) concludes the SSF has had 4.9-5.9 km of slip during the last 600,000-700,000 years that yields the exceptionally high slip-rate of 7.0-9.8 mm/yr (roughly 1/3 to 1/2 the convergence rate of the entire western Transverse Ranges, Namson and Davis, 1988). 5) Additionally to the west and east the SSF merges with the active Oak Ridge and Sierra Madre faults respectively. The recurrence time of fault movement on the SSF is presently unclear due to its poor surface exposure, extensive landslide deposits covering much of the fault zone, a wide and complex shear zone with two major splays, and limited fault trenching—all of which constrain surface-based paleoseismic knowledge. **Mitigation:** DOGGR's proposed rulemaking requires the operator to submit a risk management plan that includes risk mitigation. In general the mitigation options are limited at ACGSF and probably at other gas fields subject to fault displacement hazard: 1) As demonstrated by the ACGSF leak there is no quick and easy way to draw-down the pressure and volume of a gas storage field that has a sizable downhole leak. 2) Control of the leaking well (SS-25) took over two months, and required drilling of a relief well and a backup well. 3) Installation of downhole shut-off valves (DHSVs) on wells have been proposed at the ACGSF and other fields but the reliability of these valves is unclear especially during a nearby earthquake, and DOE and DOT have recommended doing a cost and benefit analysis of DHSVs (DOE, 2016). 4) The location of the ACGSF adjacent to urban areas of Los Angeles increases the societal impact if SSF displacement and well shearing occur plus adding an enormous legal and financial obligation to the operator. **Summary and Policy:** Society can't fix a problem by ignoring or discounting it and now is the time for the geologic community to influence new regulations being considered for the safety of gas storage fields and wells. The SSF is a recognized and regulated fault rupture hazard at the surface with a high slip rate, and if the SSF is a rupture hazard at the surface it is also a rupture hazard in the subsurface. All of the wells at the ACGSF cross the SSF and their shallow fault intersections might allow for a massive gas leakage to the surface if SSF displacement were to shear the wells. A FDHA is needed for proper fault risk assessment and mitigation plans at the ACGSF. The California Geologic Survey via the Alquist-Priolo Act regulates surface construction on and near potentially active surface faults in California and that statutory and regulatory role should be extended to subsurface fault rupture hazards. The new DOGGR Discussion Draft that identifies active faults as a hazard to gas storage wells is an important step. The California Public Utilities Commission (CPUC) regulates gas utilities' transmission and distribution pipeline systems that includes gas storage fields but its regulatory role in regard to fault displacement hazard is unclear. API RP 1171

(API, 2015) is useful but should be revised to include more guidance about fault displacement hazard and risk in seismic prone regions. PHMSA does not currently have regulations addressing underground storage, but has statutory authority over interstate and intrastate underground storage facilities (PHMSA, 2011). The 2016 PIPES Act requires PHMSA to issue, within two years, minimum safety standards for underground natural gas storage facilities. The Act allows states to adopt more stringent safety standards for intrastate facilities, if such standards are compatible with the minimum standards prescribed in the Act. Seismically active states like California should adopt standards dealing with the fault displacement risk at gas storage fields that require implementation of FDHA even if they are above the future minimum federal standards. Regulators and operators will find FDHA useful in determining whether it is safe to site gas storage fields across or near potentially active faults and reassuring the public of their decisions. Finally, there is an important role for petroleum geologists and the oil and gas industry to play in fault displacement hazard analysis and regulatory advice for gas storage fields and more broadly for earthquake hazards evaluations by virtue of their unique subsurface expertise and familiarity with deeper data sets and modern mapping and structural techniques.

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